The Littoral Sand Budget, Hawaiian Islands[1]

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ABSTRACT: Profile surveys were made across 80 selected Hawaiian beach and nearshore environments at quarterly intervals for one and one-half years during 1962–63. Also 70 additional beaches were measured at less frequent intervals. Using these profiles, supplemented by water-jet borings and measurements from aerial photographs, the total sand volume of each of the major Hawaiian beach systems was computed. The seasonal fluctuations of these volumes were also computed and related to the wave and littoral current regimes.

The volume of littoral sand was found to be considerably less than the volume for many sandy continental areas. About 4.0×10^7 cu yd of sand is held in beach reservoirs on the seven major islands of the Hawaiian group; most is concentrated on Kauai (1.4×10^7 cu yd) and on Oahu (1.0×10^7 cu yd). Individual beaches containing more than 1×10^6 cu yd are Keawanui on Niihau; Hanalei, Polihale-Barking Sands, and Kekaha-Nohili-Bonham on Kauai; Bellows-Waimanalo on Oahu; and Papohaku on Molokai. The beaches on the island of Hawaii hold the smallest volumes of sand.

Seasonal rates of erosion and accretion of beach sand reservoirs were found to be generally on the order of a few tens of cubic yards of sand per linear yard of beach per month. The higher rates were on exposed north and west coasts, with a maximum rate of several hundred cubic yards of sand per linear yard of beach per month recorded for Lumahai Beach, Kauai during 1962–63.

BEACHES ARE NOT STATIC but are continually changing their composition, structure, and volume—seasonally, yearly, or over longer periods of geologic time. Nor are these beach changes isolated phenomena. Rather, they are related, by a complex series of equilibria, with the rates of sand production, alongshore transport, and loss. Consequently, it is possible to consider a sand beach at any one moment in time to be a sand reservoir connected by certain exchanges of energy with its surrounding environment. Certain of the energy relationships between the beach and its surroundings will bring about a net increase in the volume of the beach: beach accretion. Other relationships will result in a net loss of sand from the beach: beach erosion.

In certain cases there may exist an equilibrium between accretion and erosion so that a constant beach sand volume is maintained. However, with most beaches this equilibrium is continually shifting so that the beach is continually in a state of flux, now accreting, now eroding. These fluctuations in the amount of sand held on the beach are most pronounced between seasons, reflecting the seasonal variations in the amount and types of wave energy that reach the beaches. However, diurnal, semidiurnal, and fortnightly fluctuations in beach sand volumes related to the tides, yearly and multi-yearly fluctuations related to long-period meteorological conditions, and noncyclic fluctuations, such as are caused by tsunami, are also common.

Along any stretch of coast the various factors affecting the amount of sand on the beach and in nearshore waters can be summarized, and, if the coast is in equilibrium (i.e., if a constant littoral sand volume is maintained), these factors can be quantitatively balanced against each other. Coastal streams and rivers, coastal ero-

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sion, biological activities, wind, etc., may actively contribute sand; whereas paralic sedimentation (e.g., lagoonal, shallow neritic, transportation of sand into deep water via submarine canyons), the transformation of beach sand into beach rock, and wind are factors that are responsible for the loss of beach sand.

In any one locality certain of these processes many predominate. For example, in the Hawaiian Islands beach sand is primarily acquired through the biological activities of reef organisms, and is primarily lost by paralic sedimentation. Notwithstanding the particular processes involved, if the coast is in equilibrium there must exist a qualitative balance between the rate of sand production or input and the rate of sand loss. Quantitative considerations of these rates and their effects upon the beach and nearshore sand reservoirs give rise to the concept of a *littoral sand budget,* i.e., a quantitative balance under equilibrium conditions of the rates of change and volumes of beach and nearshore sand. Basically, the littoral sand budget can be divided into three separate parts: sand input, alongshore transport, and loss. However, a fourth consideration—time—must frequently be introduced due to the fact that, although short term rates of input, alongshore transport, and loss may not balance, the coast may yet be in perfect equilibrium over longer periods of time. For an example, high rates of sand input due to heavy flooding of coastal streams may not balance with the loss of nearshore sand over the same period of time, yet the fluctuations of this sand input may be such that over long periods of time the rates of sand input, alongshore transport, and loss are in equilibrium.

Considering beaches and coasts from the viewpoint of such a littoral sand budget, it can be shown that there exist certain stretches or units of coast along which the rates of sand input, alongshore transport, and loss are in equilibrium and between which there is little or no exchange of nearshore sediment. Typically, in the Hawaiian Islands these littoral units or *littoral cells* are separated by rocky promontories or long stretches of high, nearly vertical sea cliffs around which little or no sand is transported (Fig. 1).

DISCUSSION

Littoral Sand Reservoirs

Sand-size material, contributed to the littoral sand budget by a variety of agents as discussed above, is transported into the nearshore zone, moves onto and along the beach, and after a rather long and complicated journey within the nearshore zone is finally transported out of that zone into deeper water, blown inland by the wind, or otherwise lost. Various reservoirs of sand therefore exist, corresponding to the various zones or environments through which the sand passes as it progresses toward its final depositional environment. Two types of sand reservoirs are common within the Hawaiian littoral cells: (1) the beach reservoir and (2) the nearshore reservoir, in turn composed of reef channel, reef flat, or river mouth.

BEACH RESERVOIRS (COMPARISONS): Large volumes of sand are found between mean sea level and the upper limit of wave action on two of the seven major islands of the Hawaiian group, while on the other five the total volume is extremely small. Moreover, the average volume of the beach sand reservoir per mile of sandy coastline varies greatly from island to island. The subsurface base of the beach was determined by water-jet probing; essentially it is the contact between the beach and indurated rock or cobbles. The landward limit of the beach was taken as the upper limit of wave action as determined by the beach contact with growing vegetation, sea cliffs, windblown dunes, etc. The seaward edge of the beach is mean water level. As can be seen from Table 1, more than one-third of all beach sand in the Hawaiian Islands is found on the beaches of Kauai, and more than one-fourth, on the beaches of Oahu. Together these two islands hold 61.4% of the total beach sand found in the State of Hawaii.

In order to compare the intensity and/or nature of the littoral processes of the various Hawaiian islands, it is necessary to weigh the total beach sand reservoir of each island by some parameter, such as length of coastline, which in turn can be related to the zone or area over which the littoral processes are active. Table 1 gives the average beach reservoir vol-

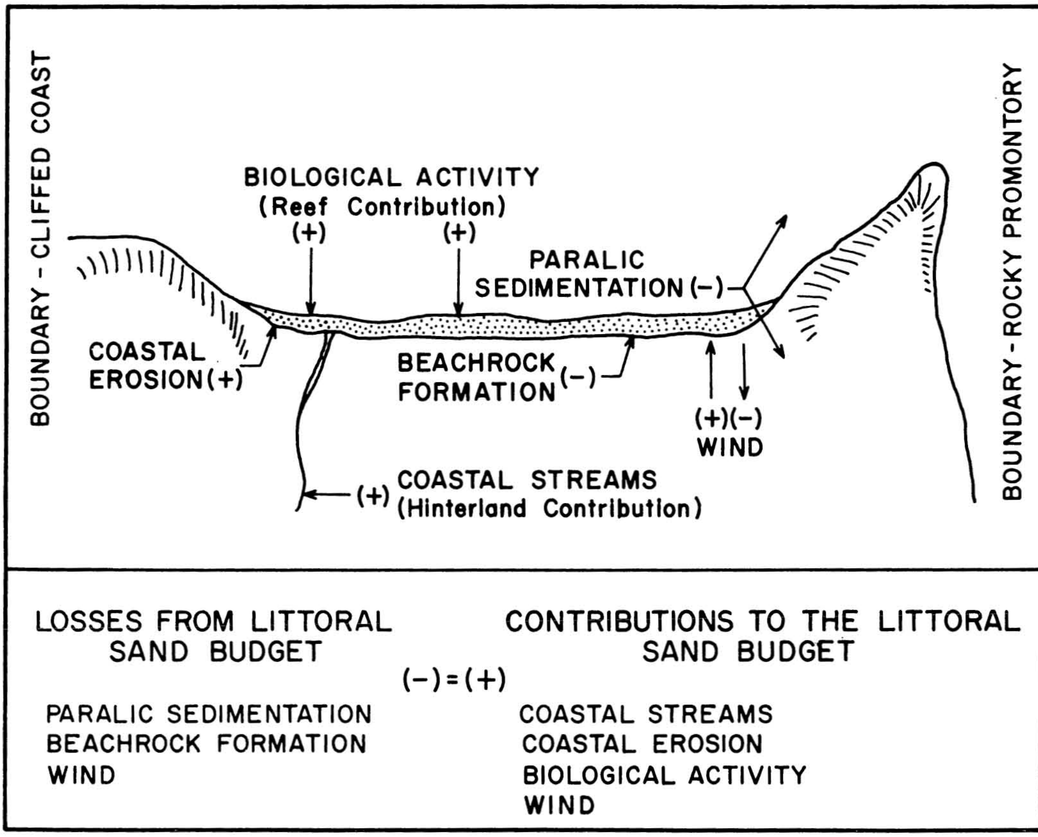

FIG. 1. Hawaiian littoral cell.

ume per mile of total coastline and per mile of sandy coastline. Comparison of these figures shows that a real difference exists between the beach sand reservoirs of the various islands. The northwesternmost islands of Niihau and Kauai have the largest beach sand reservoir per mile of coastline. This large volume of beach sand is reflected in the intensity or magnitude of littoral processes not found on the remaining islands. From Niihau and Kauai there is a general decrease, in a southeasterly direction, in the volume of the beach sand reservoir per mile of coastline. The extremely low values for the island of Hawaii indicate the low intensity of the littoral processes that produce beach sand on that island.

The average volumes of sand contained in the beach reservoirs on the island of Niihau have been computed and are presented in Table 2. The larger reservoirs are found along the northwest coast, whereas the reservoirs along the eastern coast have very little beach sand.

By far the largest sand reservoir on Kauai is at Polihale (Table 3), although those at Hanalei, Lumahai, and Wailua beaches are also fairly large. Generally, the reservoirs are larger to the west and north, and smaller along the southeastern coast. Average beach sand reservoirs computed for the remaining portions of sandy coastline are presented in Table 4.

Table 5 shows that on Oahu the largest reservoirs lie along the eastern coast adjacent to the town of Waimanalo. Other very large volumes of beach sand are located at Kahana, Maili, and Sunset Beach. Average beach sand reservoirs computed for the remaining sections of the coast are presented in Table 6.

On Molokai more than 75% of all of the beach sand is found on the western coast, principally at Papohaku (Table 7). A lesser amount is found on the northern coast in the Moomomi District, and the least on both the

TABLE 1

BEACH SAND RESERVOIRS, HAWAIIAN ISLANDS

ISLAND	TOTAL VOLUME 10^6 yd^3	MILES OF COASTLINE TOTAL	MILES OF COASTLINE SANDY	VOLUME PER MILE TOTAL COASTLINE 10^3 yd^3	VOLUME PER MILE SANDY COASTLINE 10^3 yd^3
Niihau	3.96	43.0	19.0	92.2	208.7
Kauai	13.96	113.4	41.2	123.1	338.9
Oahu	10.28	129.0*	50.3	79.7	204.4
Molokai	2.95	105.9	21.9	27.9	134 9
Lanai	1.70	52.3	18.2	32.4	93.4
Maui	5.02	158.8	32.6	31.6	153.8
Hawaii	1.68	305.5	19.4	5.5	86.5
Total	39.56			av. 56.0	av. 174.4

* Excluding Pearl Harbor, Sand Island, and parts of Kaneohe Bay.

TABLE 2

BEACH SAND RESERVOIRS, NIIHAU

COASTAL ZONE OR BEACH*	SUMMATION OF BEACH LENGTHS (yards)	AVERAGE SAND VOLUME† 10^3 yd^3
Puukole Pt.–Lehua Landing	1760	70.0
Lehua Landing–Palikoae	300	6.0
Palikoae–Keawanui	1760	17.6
Keawanui	7040	1689.0
Kaunuunui Bay	2640	396.0
Kaununui Bay–Paliuli	3520	140.8
Paliuli–Nonopapa	2000	360.0
Nonopapa–Makahauena	2640	211.2
Kamalino	100	6.0
Kahaino	100	6.0
Leahi	100	6.0
Kawaihoa–Oiamoi	1760	105.6
Oiamoi–Poooneone	1760	211.2
Poooneone–Poleho	2640	316.8
Poleho–Kii	3520	316.8
Kii–Puokola	1760	105.6

* Listed counterclockwise from northwestern coast of island.
† Volumes obtained from a single set of profiles in 1963, supplemented by aerial photographs and maps.

northeastern and southeastern coasts. Average beach sand reservoirs were computed for the remaining sections of the coast (Table 8).

Almost all of the beach sand on Lanai is found along the northern and eastern coasts (Table 9), and at Polihua, the largest single reservoir, the volume is more than ½ million cubic yards. Average beach sand reservoirs for the remaining sections of the coast are given in Table 10.

The largest beach sand reservoirs on Maui (Table 11) are found on the southwestern coast of Haleakala, on the northern coast near Sprecklesville, and along the western coast of West Maui (Table 12). The entire eastern coastal portion of East Maui is nearly lacking in sand.

The beach sand reservoirs are extremely small on the island of Hawaii (Tables 13 and 14); Waipio and Hapuna are the only beaches where the sand volume exceeds 100,000 cubic yards. The northwest section of the island, especially just south of Kawaihae, has the largest reservoirs. Along the flanks of Mauna Loa and Kilauea volcanoes few beaches are present.

NEARSHORE RESERVOIRS: The sand-size particles moving thorugh the littoral sand system may be deposited temporarily in one of several littoral environments other than that of the beach.

Reef Channel. Particles produced by the attrition of reef flora and fauna frequently are transported through a complex series of reef environments before being brought onto the beach, and even after reaching the beach they may be transported back and forth seasonally between the beach and reef before they are finally carried out of the littoral zone into deep water, or blown inland by the wind, or otherwise lost. Any channel or depression across the nearshore zone acts as a trap for this littoral sand.

Around the Hawaiian Islands the fringing

TABLE 3

BEACH SAND RESERVOIRS, SELECTED BEACHES, KAUAI

BEACH*	SAND VOLUME, 10^3 yd^3 5/62	8/62	11/62	2/63	5/63	8/63	AVERAGE
Kalihiwai	441.6	370.8	277.8	202.8	358.2	501.6	358.8
Anahola	234.0	270.9	242.1	252.9	196.2	205.2	233.6
Kapaa	40.8	47.2	37.6	32.0	36.8	43.2	39.6
Wailua	705.7	560.3	593.3	530.3	705.7†	185.3	546.8
Nawiliwili	61.6	49.7	51.5	44.4	46.2	56.8	51.7
Poipu	15.2	6.5	6.5	9.9	11.8	12.9	10.5
Hanapepe	126.0	166.6	126.7	104.3	71.4	30.1	104.2
Waimea	433.0†	286.9	343.2	431.2	433.0	569.4	416.1
Kekaha	12.8	80.0	68.8	294.4	124.8	120.0	116.8
Polihale	2386.6	3136.3	3073.0	4836.5	3791.0	3917.8	3523.5
Maninihola	124.3	133.0	122.5	120.0	138.2	140.4	129.4
Lumahai (W)	881.3	959.0	468.3	147.7	710.5	832.3	666.5
Lumahai (E)	95.5	79.0	147.8	387.0	89.5	94.0	148.8
Hanalei	1910.6	1739.0	1278.4	1024.6	1160.9	1339.5	1408.8

* Listed clockwise from northern coast of island.
† Assumed value, based on measurement at comparable season.

coral reefs are cut by numerous channels, some of which are surge channels that carry the water from the breaking waves up onto the reef flat. Other, often broader channels are frequently sites of old river courses across the reef (Fig. 2). Large volumes of sand are found in these channels. Most of the sand is newly formed material from the adjacent reefs and is in the process of being carried shoreward into the beach system. However, there exist definite sand circulatory patterns on the reefs, and some of the larger channels act as routes for the transportation of beach sand into deep water. Still others of the reef channels during certain seasons supply sand to the beach, and during other seasons receive sand from the beach so that a sand exchange system exists between the channels and the beach.

Notwithstanding the type or direction of movement, the sand found in the nearshore reef channels represents an important sand reservoir, the volume of which fluctuates seasonally,

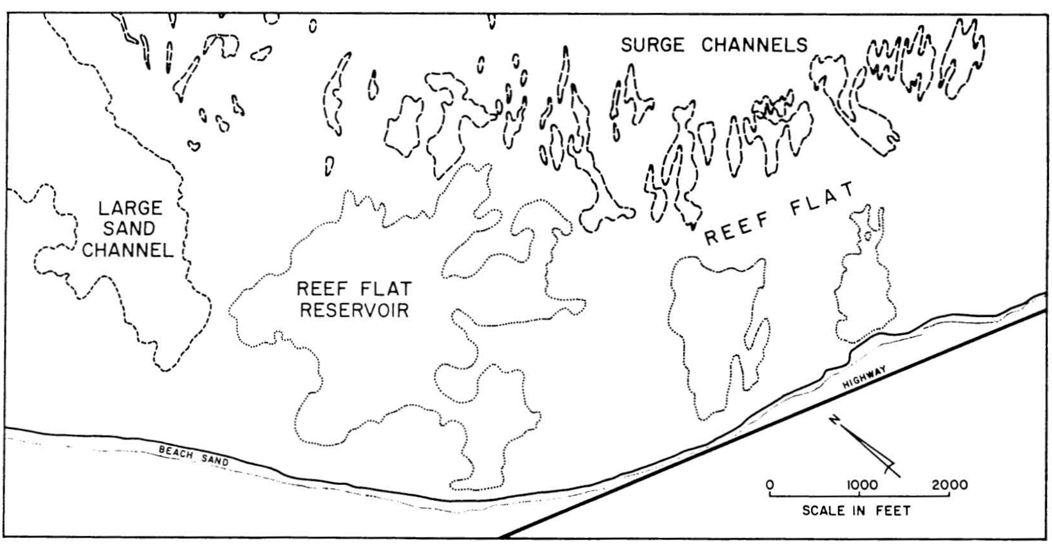

FIG. 2. Reef flat and channels, Waimanalo, Oahu.

TABLE 4

BEACH SAND RESERVOIRS, MISCELLANEOUS COASTAL ZONES, KAUAI

COASTAL ZONE*	SUMMATION OF BEACH LENGTHS (yards)	AVERAGE SAND VOLUME† 10^3 yd^3
Lae o Kaweonui–Kalihiwai	4000	160.0
Kalihiwai–Moloaa	5765	691.8
Moloaa	700	84.0
Moloaa–Anahola	1965	78.6
Anahola–Kealia	1700	102.0
Kealia	1100	220.0
North Kapaa	1000	20.0
South Kapaa	1210	24.2
South Kapaa–Wailua	1925	38.5
Wailua–Hanamaulu	4450	267.0
Hanamaulu	500	30.0
Nawiliwili–Poipu	4820	289.2
Waiohai	450	18.0
Poipu–Hanapepe	2080	83.2
Hanapepe–Makaweli	950	38.0
Makaweli	1340	53.6
Makaweli–Waimea	2815	112.6
Waimea (Pier–Boat Harbor)	2580	103.2
Kekaha	2300	230.0
Kekaha–Bonham	8750	1750.0
Na Pali	4700	188.0
Ka Lae o Kailio	350	14.0
Ka Lae o Kailio–Haena	1650	66.0
Maninihola–Kepuhi	2665	799.5
Kepuhi	420	12.6
Wainiha	450	67.5
Middle Lumahai	250	25.0
Makahoa–Waioli Stream	1335	560.7
Hanalei River–Lae o Kaweonui	1380	82.8

* Listed clockwise from northern coast of island.
† Volumes obtained from a single set of profiles in 1963, supplemented by aerial photographs and maps.

yearly, or otherwise, in response to waves and currents. An intimate and complex relationship exists between the various nearshore sand reservoirs and the beach reservoir; in some cases it can be shown that increases in the beach sand volumes are accompanied by decreases in the offshore reef channel reservoirs and vice versa.

The actual volume of the various reef channel reservoirs varies greatly. Surge channels extending up across the front of the reef may have a thickness of from 1 to 4 ft of sand and individual channels may contain several hundreds of cubic yards. Accurate volume measurements involving subsurface probing have shown that the summation of sand channel volumes along the entire front of a typical, small, Hawaiian reef between the depth ranges of —40 to —5 ft MLLW amounts to a sand reservoir of somewhat more than 50,000 cubic yards per linear mile of reef. On a large reef this volume may be nearer 200,000 cubic yards per linear mile.

The largest channels across the reef, some of which are ancient river courses, contain reservoirs of sand that are measured in millions of cubic yards. For example, the sand reservoir of the Halekulani Channel crossing Waikiki Reef, Oahu, has been measured and found to contain nearly ½ million cubic yards of sand within the depth range of 0–30 ft MLLW. Accurate measurements including subsurface probings of the sand channel reservoir in Pokai Bay, Oahu, indicate a reservoir volume of between 1 and 2 million cubic yards out to a water depth of 30 ft MLLW.

Reef Flat. There exist numerous shallow depressions on the reef flats surrounding the Hawaiian Islands. Many of these are measured in hundreds or in thousands of square yards, and quite a few are measured in hundreds of thousands of square yards. Most of the sand produced on the reef flat is transported onto the beach by being moved in a series of steps from one of these depressions, or sand pockets, to another. Consequently, the reef flat reservoirs also play an important role in the littoral sand budget.

Most of the sand reservoirs on the reef flat are shallow, sand thickness being measured in feet; individual sand pockets may contain only a few hundred or a few thousand cubic yards of sand. But when the sand pocket volumes are summed over an extensive reef, such as the Sprecklesville Reef, Maui, or the Waimanalo Reef, Oahu, the total indicates a reservoir of several millions of cubic yards of sand per square mile of reef.

These large volumes of sand located near shore and generally in water depths of less than 12 ft are very susceptible to varying wave and current conditions. Under certain wave conditions the rapid rates of accretion of the Hawaiian beaches is entirely due to the avail-

TABLE 5

BEACH SAND RESERVOIRS, SELECTED BEACHES, OAHU

BEACH*	SAND VOLUME, 10^3 yd^3						
	5/62	7/62	11/62	3/63	5/63	8/63	AVERAGE
Laie	197.2	219.3	180.2	221.0	205.7	163.2	197.8
Hauula (N)	26.0	20.0†	22.7	40.0	21.3	18.0	24.7
Hauula	13.0†	17.8	15.4	14.4	13.0	14.9	14.8
Punaluu	59.0†	64.2	59.8	66.9	59.0	56.3	60.9
Kahana	305.8†	305.8	444.4	522.5	500.0†	496.1	429.1
Kailua (N)	74.0	97.5	114.0	89.3	85.8	134.0	99.1
Kailua	35.2	55.2	52.9	70.5	49.4	45.8	51.5
Kailua (S)	37.6	45.8	70.5	95.2	67.0	99.9	69.3
Lanikai (S)	170.2	179.4	177.6	192.4	112.8	198.0	171.7
Waimanalo	942.2	981.7	704.6	823.9	650.6	746.9	808.3
Waimanalo (S)	254.1	284.9	157.8	146.3	219.4	304.2	227.8
Makapuu	19.6	35.0	36.0	32.0	10.6	18.0	25.2
Sandy Beach	142.0	138.0	101.0	132.5	112.0	106.5	122.0
Kahala	29.1†	31.2	25.0	35.4	29.1	37.4	31.2
Natatorium	11.5†	10.7	9.0	21.3	11.5	10.2	12.4
Kuhio	76.8†	91.2	79.2	80.4	76.8	85.2	81.6
Ewa	174.0	195.0	177.0	123.0	123.0	138.0	155.0
Kalanianaole	24.0	82.8	33.9	29.2	43.2	43.1	42.7
Maili	933.9	897.6	828.3	504.9	699.6	848.1	785.4
Pokai	32.8	40.0	35.6	30.2	30.4	41.6	35.1
Makaha	148.1	191.6	138.0	33.5	76.4	116.6	117.4
Keawaula	24.0	238.8	81.6	43.2	182.4	247.2	136.2
Camp Erdman	92.4†	93.8	79.8	109.2	92.4	95.2	93.8
Mokuleia	32.0†	61.0	69.0	35.0	32.0	46.0	45.8
Waialua	5.8†	4.2	3.9	4.9	5.8	7.0	5.3
Kawailoa	66.0†	71.4	52.2	41.4	66.6	76.2	62.4
Waimea	109.4	96.2	85.5	99.0	45.6	53.9	81.6
Sunset	241.6	417.6	273.6	406.4	376.0	393.6	351.5

* Listed clockwise from northeast coast of island.
† Assumed value.

ability of this reef flat reservoir and the rapid transport of sand from it onto the beach.

River Mouth. Sand-size material derived from the erosion of the hinterland is transported by streams and rivers to the ocean. Following initial deposition at the mouth of the streams and rivers, much of the sand is moved along through the littoral system on and off the beach and eventually is carried out into deep water, blown inland, or otherwise lost.

In the Hawaiian Islands the largest river-mouth sand reservoir is off the Waimea River, Kauai. The exact volume of this reservoir is not known, but subsurface probings have shown that over an area of about one square mile off the Waimea River the sand thickness is greater than 20 ft. Consequently, a sand reservoir on the order of 10^7 cubic yards is indicated.

Smaller river mouth reservoirs are found off several other Hawaii rivers, notably Hanapepe and Hanalei, Kauai.

Selected Beaches. Whereas an accurate volume measurement of the total beach sand reservoir for the Hawaiian Islands was fairly easily obtained, similar measurement for the total nearshore sand reservoir was not possible. The difficulty lay in obtaining a sufficient number of submarine measurements, compounded by surf and current conditions that in many localities prevented direct bottom measurements. Consequently, it was possible to measure only portions of the nearshore sand reservoir off certain selected beaches. The integration of these limited data over extended lengths of the coast is prevented by the extreme variability of the size of sand channels and sand pockets. At best the data can be used to indicate the relative vol-

TABLE 6

BEACH SAND RESERVOIRS, MISCELLANEOUS COASTAL ZONES, OAHU

COASTAL ZONE*	SUMMATION OF BEACH LENGTHS (yards)	AVERAGE SAND VOLUME† 10^3 yd^3
Kahuku–Laie	7000	700.0
Laie–N. Hauula	2100	210.0
N. Hauula–Hauula Park	685	41.1
Hauula Park–Punaluu	4500	270.0
Kahana–Kuloa	3800	152.0
Kaneohe Bay–Mokapu	2950	118.0
Kailua	1175	105.8
Kaupo Beach Park	1850	18.5
Makapuu–Sandy Beach	700	28.0
Sandy Beach–Portlock	600	12.0
Portlock–Kahala	7300	146.0
Kahala–Natatorium	2300	92.0
Halekulani–Pearl Harbor	3500	140.0
Oneula	300	36.0
Oneula–Kalanianaole Park	7600	912.0
Nanakuli	2840	568.0
Maili–Pokai	600	54.0
Pokai–Makaha	2050	307.5
Makaha–Keawaula	5400	540.0
Keawaula–Camp Erdman	1500	180.0
Camp Erdman–Mokuleia	3500	280.0
Mokuleia–Waialua	7400	592.0
Waialua Bay	400	16.0
Waialua–Kawailoa	900	36.0
Kawailoa–Waimea	830	33.2
Sunset	1600	128.0
Sunset–Kahuku	3600	216.0

* Listed clockwise from northeastern coast of island.
† Volumes obtained from a single set of profiles in 1963, supplemented by aerial photographs and maps.

ume of the nearshore sand reservoirs off certain coasts of the Hawaiian Islands.

In Table 15 the nearshore sand reservoir computed in cubic yards of sand per linear yard of beach is given for 83 selected beaches in the Hawaiian Islands. Since it was impossible to measure this sand volume to a similar water depth off all beaches, the limiting depth of water is also tabulated. In most cases no sand existed seaward of the limiting depth so that the volumes listed represent the total nearshore sand reservoir per linear yard of beach for that particular beach. (In other cases, however, additional volumes of sand exist seaward of the limiting depth so that the volumes in some cases are minimal.)

The largest nearshore sand reservoirs on the island of Kauai are off the major rivers, Waimea, Hanapepe, and Waialua, and in Hanalei and Nawiliwili bays. The total nearshore sand reservoir around the island of Kauai is probably in excess of 25 million cubic yards of sand, i.e., more than twice the total beach sand reservoir for this island.

The largest nearshore sand reservoirs on the island of Oahu are in Kahana and Pokai bays. On this island, the total nearshore reservoir is probably approximately equal to the beach sand reservoir, i.e., 10^7 cubic yards.

Except for the reservoirs off Papohaku and Moomomi, very little nearshore sand exists around the island of Molokai. The total volume may be between 1 and 2 million cubic yards.

TABLE 7

BEACH SAND RESERVOIRS, SELECTED BEACHES, MOLOKAI

BEACH*	SAND VOLUME, 10^3 yd^3						
	6/62	8/62	11/62	3/63	6/63	9/63	AVERAGE
Halawa	21.9†	21.9	20.0	19.0	21.9	22.4	21.2
Kanaha	2.4	2.2	2.5	2.8	2.8	2.6	2.6
Onealii	1.4	2.0	2.0	1.4	1.4	1.6	1.6
Kapukuwahine	122.5	94.3	94.3	2.3	29.9	75.3	69.8
Kamakaipo	83.2†	71.5	78.0	59.8	83.2	80.6	76.0
Papohaku	1505.0	1100.5	782.8	623.1	880.4	813.8	950.9
Kepuhi	41.5	52.8	50.8	28.0	43.0	48.5	44.1
Kawaaloa	169.8	187.8	72.0	184.8	147.6	159.3	153.6

* Listed clockwise from the northeastern coast of island.
† Assumed value.

TABLE 8

BEACH SAND RESERVOIRS, MISCELLANEOUS COASTAL ZONES, MOLOKAI

COASTAL ZONE*	SUMMATION OF BEACH LENGTHS (yards)	AVERAGE SAND VOLUME† 10^3 yd^3
Kahiu–Halawa	400	24.0
Halawa	250	10.0
Halawa–Kanaha	100	4.0
Kanaha–Honouliwai	150	6.0
Honouliwai	150	6.0
Honouliwai–Kalaeloa	7500	75.0
Kalaeloa–Onealii	6375	63.8
Onealii–Kamehameha	4750	47.5
Kamehameha–Hale o Lono	7250	72.5
Hale o Lono–Kapukuwahine	360	14.4
Kapukuwahine	1275	76.5
Kapukuwahine–Laau	1100	66.0
Kamakaipo–Kaunalu	100	6.0
Kaunalu	150	12.0
Kaunalu–Papohaku	300	36.0
Papohaku	1550	775.0
Kepuhi	425	106.2
Kepuhi–Ilio	800	120.0
Kapalauoa–Kawaaloa	1725	69.0
Kawaaloa	300	45.0
Moomomi	100	25.0
Puwahi	950	76.0
Kalaupapa	600	48.0

* Listed clockwise from northeastern coast of island.
† Volumes obtained from a single set of profiles in 1963, supplemented by aerial photographs and maps.

Around the island of Lanai the nearshore sand reservoirs are also very small. The largest is off Polihua but the total volume probably does not exceed 10^6 cubic yards.

On Maui large nearshore sand reservoirs exist in Hana Bay and off Honokahua and Kihei, and a total nearshore sand reservoir equal to the total beach sand reservoir seems probable, i.e., 5×10^6 cubic yards.

On Hawaii there are small nearshore sand reservoirs in Waipio Bay and off Kailua, Hapuna, and Kawaihae, probably not exceeding 10^6 cubic yards.

Seasonal Fluctuations

In tropical latitudes such as the Hawaiian area, the climatic year is not divided into four but rather into two natural meteorological seasons. Winter is well defined by the weakening of the northeast trade winds and the appearance of southwesterly winds. During the summer (April through November), strong trades blow from the eastern and northern quadrants, or transitional wind conditions exist.

During 1962–63 southwesterly or westerly winds dominated the local weather from November 1962 to April 1963 (Fig. 3). The remaining months of these two years, except for January and February, 1962, and December 1963, were exclusively under the influence of northeasterly trade winds.

The seasonal fluctuations of the beach sand reservoir for each of the 76 selected beaches as given in Tables 3, 5, 7, 9, 11, and 13, are summarized by island in Figure 4. Although the selected beaches represented in this figure do not include the entire beach sand reservoir, they are well distributed geographically on each island so that the total accretion or erosion as indicated, while not representing the total magnitude of change for each island, does represent quite accurately the direction of change, i.e., total island accretion or erosion.

On certain of the islands (e.g., Molokai and

TABLE 9

BEACH SAND RESERVOIRS, SELECTED BEACHES, LANAI

BEACH*	SAND VOLUME, 10^3 yd^3 6/62	9/62	12/62	4/63	AVERAGE
Halulu	7.7†	28.7	1.4	7.7	11.4
Hauola	18.4	9.6	17.6	17.2	15.7
Hulopoe	77.4	74.7	70.6	74.2	74.2
Polihua	532.8	516.8	321.6	320.0†	422.8

* Listed clockwise from the northeastern coast of island.
† Assumed value.

TABLE 10

BEACH SAND RESERVOIRS, MISCELLANEOUS COASTAL ZONES, LANAI

COASTAL ZONE*	SUMMATION OF BEACH LENGTHS (yards)	AVERAGE SAND VOLUME† 10^3 yd^3
Kuahua–Halulu	2300	92.0
Halulu–Hauola	5800	232.0
Hauola–Kapoho	10,700	428.0
Manele	500	30.0
Manele–Hulopoe	75	4.5
Polihua–Hale o Lono	1600	192.0
Hale o Lono–Kuahua	4800	192.0

* Listed clockwise from northeastern coast of island.
† Volumes obtained from a single set of profiles in 1963, supplemented by aerial photographs and maps.

Lanai), where the distribution of the beaches is skewed toward one particular area, the fluctuations of the total beach reservoir reflect quite clearly the fluctuating wind, wave, and current conditions. However, on other islands (e.g., Kauai and Oahu) with nearly 360-degree distribution of beaches, erosion of the beaches along one coast may be accompanied by accretion of the beaches on the opposite side of the island due to the sheltering effects of the island itself. Under these conditions it is not possible to deduce the relationship between the beach reservoir and the meteorological and oceanographic conditions from the total island beach reservoir fluctuations. Individual beach sand reservoir changes must be studied.

RATES OF ACCRETION AND EROSION IN BEACH SAND RESERVOIRS: As can be seen from Table 16, there are several beaches on Kauai, notably Lumahai, where the rates of beach erosion and accretion are on the order of several hundreds of cubic yards of sand per linear yard of beach per month.

When the data are grouped according to island sectors, it can be seen that the effects of the winter storms are not the same in all island sectors (Fig. 5). Under Kona (southwesterly wind) conditions the northern beaches rapidly erode, but with the cessation of the westerly winds and the start of the northeast trades these same beaches rapidly accrete. The opposite is true of the beaches in the southern sector. With the commencement of winter storms, Polihale, Kekaha, Waimea, and the

TABLE 11

BEACH SAND RESERVOIRS, SELECTED BEACHES, MAUI

BEACH*	SAND VOLUME, 10^3 yd^3						
	4/62	6/62	9/62	2/63	6/63	9/63	AVERAGE
Hana	23.8	16.3	22.6	19.6	18.2	23.1	20.6
Hamoa	32.3†	48.6	47.0	32.3	31.0	43.6	39.1
Puu Olai	366.3	364.1	365.2	526.9	408.1	364.1	399.1
Makena	12.3	23.0	4.3	9.6	10.9	7.6	11.3
Keawakapu	44.1	52.2	60.3	10.8	48.6	63.0	46.5
Kalama	116.4	109.3	92.6	95.0	90.2	104.5	101.3
Kihei	294.2	217.9	188.0	118.5	226.1	217.9	210.4
Maalaea	250.6	226.0	191.8	231.2	194.5	248.9	223.8
Olowalu	264.0	221.8	209.4	262.2	169.0	213.0	223.2
Makila	2.4	2.4	2.2	1.6	1.6	4.6	2.5
Hanakaoo	85.5	34.5	25.5	43.5	22.5	30.0	40.3
Kaanapali	92.0†	106.5†	101.2	92.0	106.5	117.9	102.7
Napili	28.6†	71.6	51.9	28.6	48.6	63.9	48.9
Fleming's	9.8†	4.6	7.4	9.8	7.8	8.8	8.0
Honokahua	53.5	66.5	71.5	57.5	82.5	59.5	65.2
Wai Paoko Kaio	31.8	45.2	48.6	48.6	46.9	46.9	44.7
Kahului Harbor	104.0†	123.4	76.6	104.0	92.9	84.0	97.5
Kahului	244.7	202.2	243.2	326.8	252.3	310.1	263.2
Papaula	148.4	176.4	165.9	125.3	149.1	129.5	149.1
Paia	44.2	39.8	44.2	36.8	42.0	53.7	43.0

* Listed clockwise from eastern coast of island.
† Assumed value.

TABLE 12

BEACH SAND RESERVOIRS, MISCELLANEOUS COASTAL ZONES, MAUI

COASTAL ZONE*	SUMMATION OF BEACH LENGTH (yards)	AVERAGE SAND VOLUME† 10^3 yd^3
Opana–Hana	1300	52.0
Hana–Hamoa	600	54.0
Hamoa–Puu Olai	1100	44.0
Puu Olai–Makena	110	9.9
Keawakapu–Kalama	1550	139.5
Waipuilani–Maalaea	2724	408.6
Maalaea–Papawai	150	6.0
Papawai–Olowalu	1420	85.2
Olowalu–Launiupoko	1100	99.0
Launiupoko–Hahakea	4620	554.4
Hahakea–Hanakaoo	1500	90.0
Kaanapali–Napili	5300	477.0
Fleming's–Honokahua	385	34.6
Waihee–Wai Paoko Kaio	2830	113.2
Wai Paoko Kaio–Kahului	2400	144.0
Kahului–Spreckelsville	2100	252.0
Spreckelsville–Paia	1950	234.0
Paia–Opana	650	78.0

* Listed clockwise from northern coast of island.
† Volumes obtained from a single set of profiles in 1963, supplemented by aerial photographs and maps.

other beaches along the southwestern and southern coast begin to accrete, and with the return of the northeast trades they undergo erosion. The behavior of the eastern beaches is not as clear; during the duration of the study they were generally eroding, but the data are incomplete.

When the rates of accretion and erosion of 28 Oahu beaches (Table 17) were grouped into island sectors, the seasonal variation in the beach sand reservoirs was readily apparent (Fig. 6). With the commencement of winter Kona storms, the western beaches (leeward with regard to the northeast trades) erode rapidly. At the same time the beaches on the eastern side of Oahu accrete. With the cessation of the westerly storms and the return of the northeast trades, the process reverses. The northern beaches follow the same pattern as the windward ones, accreting under Kona conditions and eroding under normal trade wind conditions.

On Molokai, extremely rapid rates of change were measured at Kawaaloa and Papohaku (Table 18). Because nearly the entire beach sand reservoir is concentrated along the western sector of Molokai, the total Molokai beach reservoir fluctuates in a manner similar to the western sector reservoirs of Oahu and Kauai. With the commencement of Kona storms the Molokai beaches erode, and, during the periods of northeast winds and waves, they accrete (Fig. 4).

On Lanai, low rates of change are indicated, except possibly at Polihua (see Table 19). Because the major beach reservoirs are on the western end of Lanai, the Lanai beaches also fluctuate in phase with those of Molokai and of the western sectors of Oahu and Kauai. With the commencement of Kona conditions, erosion occurs. Under the northeastern winds and waves the beaches accrete (Fig. 4).

TABLE 13

BEACH SAND RESERVOIRS, SELECTED BEACHES, HAWAII

BEACH*	SAND VOLUME, 10^3 yd^3 4/62	6/62	9/62	1/63	4/63	7/63	AVERAGE
Waipio	372.3	198.0	120.1	169.0	242.9	71.3	195.6
Hilo	6.5†	4.0	4.5	5.5	6.5	5.5	5.4
Kaimu	16.0†	11.0	11.0	6.3	16.0	5.3	10.9
Punaluu	8.8†	9.8	9.6	9.0	8.8	10.1	9.4
Hookena	15.0†	17.8	17.6	15.4	15.0	14.3	15.9
Kealakekua	3.5	3.5	2.3	1.4	1.6	1.9	2.4
Disappearing Sands	1.8	3.8	3.4	0.8	0.7	2.2	2.1
Hapuna	131.5	127.0	104.0	102.5	89.0	129.5	113.9
Kawaihae	4.6	4.1	4.5	4.1	4.1	3.4	4.1

* Listed clockwise from northern coast of island.
† Assumed value.

TABLE 14

BEACH SAND RESERVOIRS, MISCELLANEOUS COASTAL ZONES, HAWAII

COASTAL ZONE*	SUMMATION OF BEACH LENGTHS (yards)	AVERAGE SAND VOLUME† 10^3 yd^3
Upolu–Pololu	100	12.0
Pololu	525	63.0
Pololu–Waipio	515	61.8
Hilo–Kaimu	300	18.0
Kaimu–Punaluu	400	16.0
Punaluu–Hookena	1000	120.0
Hookena–Napoopoo	30	2.4
Kealakekua–Disappearing Sands	200	24.0
Disappearing Sands–Hapuna	5500	825.0
Hapuna–Kawaihae	500	75.0

* Listed clockwise from northern coast of island.
† Volumes obtained from a single set of profiles in 1963, supplemented by aerial photographs and maps.

On Maui, rates of change are low, measured in a few cubic yards of sand per linear yard of beach per month (Table 20). Whereas most of the other Hawaiian islands are directly exposed to the waves generated by the southerly and westerly winds, Maui is protected in that quarter by the islands of Kahoolawe and Lanai, and a little to the northwest, by Molokai. Consequently, the refraction of waves around these obstacles, in addition to the direction of wave approach, plays an important part in determining the amount of energy reaching the coast. Because of this consideration the fluctuations of the various beach sand reservoirs do not show any simple relationship to the gross meteorological spectrum detailed in Figure 3. Relationships undoubtedly exist—since the seasonal volumes of the total beach reservoir show marked fluctuations, accreting during the winter storm and subsequently eroding under northwesterly winds and waves (Fig. 4)—but the exact nature of this fluctuation is not clear.

On Hawaii, rates are extremely low with the exception of Hapuna and Disappearing Sands (Table 21). But although the data are scattered and the total sand reservoir is low (lowest of all the islands) it is still possible to discern a pattern of behavior—similar to that for the western beaches of Oahu and Kauai—for Hapuna, Kawaihae, Kailua, and other western beaches. On the other hand during the winter storms of 1962–63, Waipio Beach accreted at the rate of about 9 cubic yards of sand per linear yard of beach per month, and, with cessation of the westerly winds and the com-

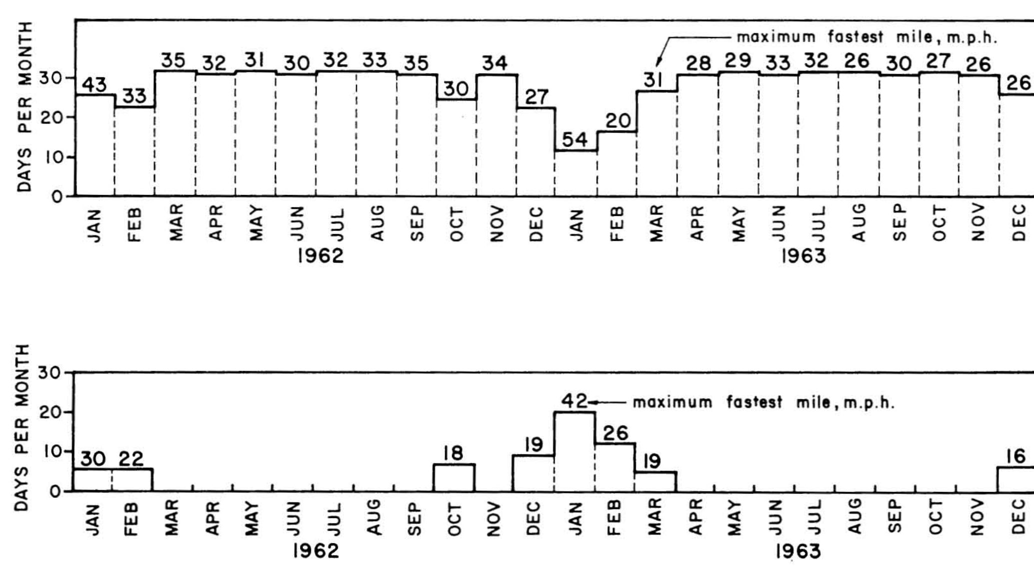

FIG. 3. Dominant winds, 1962–63. *Upper,* number of days per month that winds blew from the northern, eastern, and southern quadrants. *Lower,* number of days per month that winds blew from the southern and western quadrants.

TABLE 15

NEARSHORE SAND RESERVOIRS, SELECTED BEACHES, HAWAIIAN ISLANDS

BEACH	LIMITING DEPTH OF VOLUME COMPUTED (feet)	CU YD OF SAND PER LINEAR YD OF BEACH*
KAUAI		
Kalihiwai	30	1011
Anahola	30	762
Kapaa	6	16
Wailua	35	1092
Nawiliwili	45	2674
Poipu	34	60
Hanapepe	33	1978
Waimea	38	3359
Kekaha	19	10
Polihale	42	1369
Maninihola	40	373
Lumahai (W)	43	1651
Lumahai (E)	51	2264
Hanalei	43	2735
OAHU		
Laie	8	12
Hauula (N)	9	16
Hauula (S)	3	4
Punaluu	3	23
Kahana	33	6942
Kailua (N)	8	22
Kailua	11	127
Kailua (S)	5	21
Lanikai (S)	7	15
Waimanalo (N)	16	459
Waimanalo (S)	7	29
Makapuu	29	194
Sandy Beach	12	33
Kahala	2	17
Natatorium	6	5
Kuhio	5	53
Halekulani	22	1187
Ewa	4	14
Kalanianaole	11	64
Maili	16	73
Pokai	44	2329
Makaha	52	2205
Keawaula	15	46
Erdman	8	7
Mokuleia	9	11
Waialua	38	94
Kawailoa	6	6
Waimea	28	279
Sunset	21	118
MOLOKAI		
Halawa	12	31
Kanaha	3	0
Onealii	2	7
Kapukuwahine	33	17
Kamakaipo	10	0
Papohaku	24	836
Kipuhi	35	34
Kawaaloa	30	573
LANAI		
Halulu	6	19
Hauola	4	45
Hulopoe	23	45
Kaena	18	17
MAUI		
Hana	30	2603
Hamoa	28	62
Puu Olai	35	180
Makena	36	70
Wailea	30	552
Kalama	3	18
Kihei	34	1862
Maalaea	23	192
Olowalu	23	76
Makila	30	0
Hanakaoo	35	10
Kaanapali	40	107
Napili	29	161
Fleming's	40	246
Honokahua	51	2453
Wai Paoko Kaio	3	0
Kahului Harbor	17	973
Kahului	9	59
Papaula	5	79
Paia	12	97
HAWAII		
Waipio	8	280
Hilo	18	57
Kaimu	8	5
Punaluu	6	0
Hookena	33	50
Kealakekua	60	0
Kailua	33	365
Hapuna	29	375
Kawaihae	10	188

* Volumes obtained from aerial photographs, seasonal profiles, and water-jet probings.

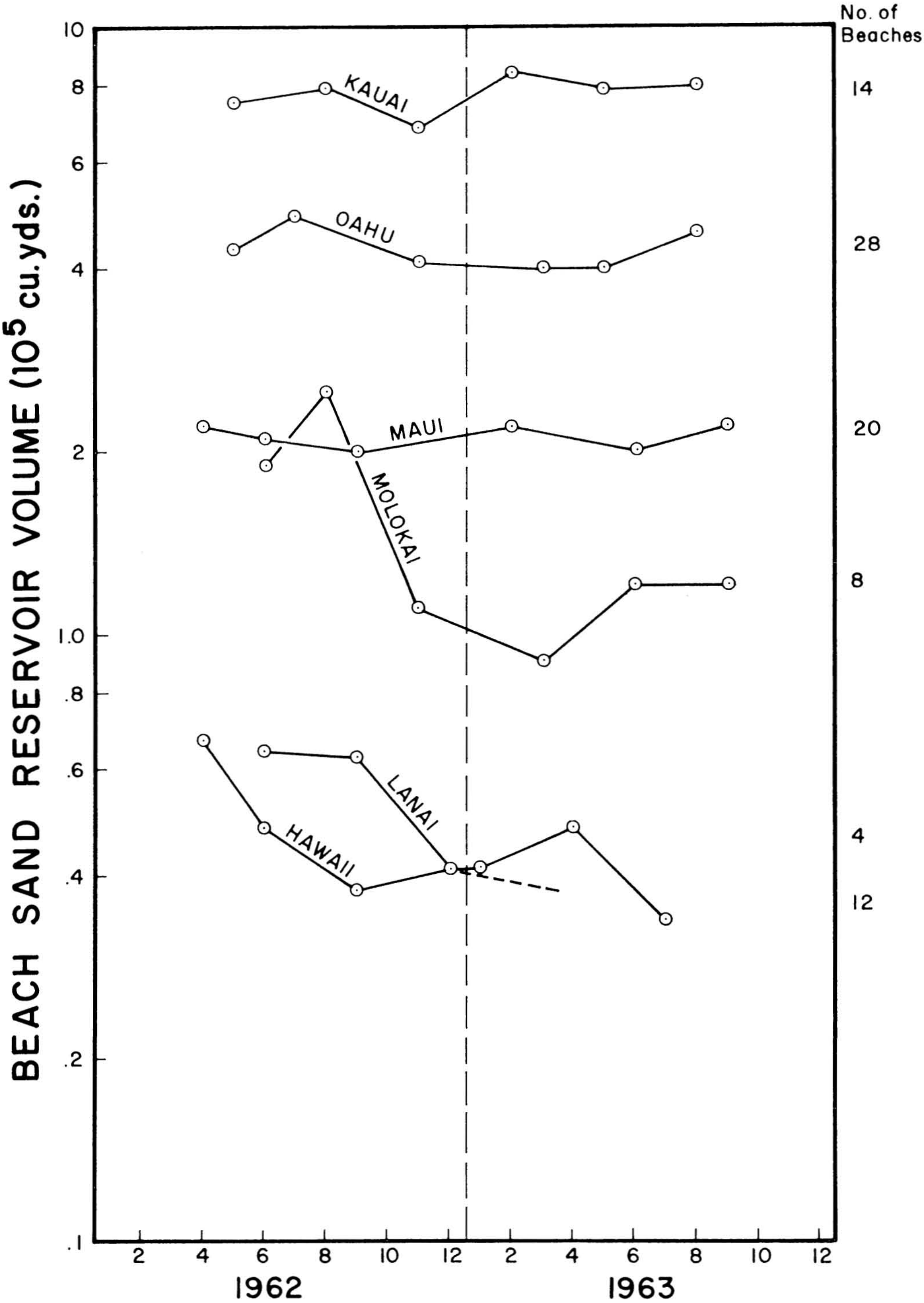

FIG. 4. Seasonal fluctuations in beach sand reservoirs, selected beaches, Hawaiian Islands.

TABLE 16

RATES OF ACCRETION AND EROSION ON SELECTED BEACHES, KAUAI*

BEACH	SECTOR	BEACH LENGTH (yards)	5/62–8/62 (3 mos.)	8/62–11/62 (3 mos.)	11/62–2/63 (3 mos.)	2/63–5/63 (3 mos.)	5/63–8/63 (3 mos.)
Kalihiwai	northern	600	−36.0	−51.6	−41.6	+86.3	+79.6
Anahola	eastern	900	+13.3	−10.6	+4.0	−21.0	+3.1
Kapaa	eastern	800	+2.6	−4.0	−2.3	+2.0	+2.6
Wailua	eastern	750	−64.6	+14.6	−28.0	†	†
Nawiliwili	eastern	440	−9.0	+1.3	−5.3	+1.3	+8.0
Poipu	southern	380	−7.6	0	+3.0	+1.6	+1.0
Hanapepe	southern	700	+19.3	−19.0	−10.6	−15.6	−19.6
Waimea	southern	880	†	+21.3	+33.3	+0.6	+51.6
Kekaha	southern	2300	−10.6	−2.3	+47.0	−35.1	−1.0
Polihale	southern	5280	+47.3	−4.0	+111.3	−66.0	+8.0
Maninihola	northern	350	+8.3	−10.0	−2.3	+17.3	+2.0
Lumahai (W)	northern	700	+37.0	−233.6	−152.6	+268.0	+58.0
Lumahai (E)	northern	250	−22.0	+91.6	+315.6	−396.6	+6.0
Hanalei	northern	2350	−24.3	−65.3	−36.0	+19.3	+25.3

* Rates of accretion (+) and erosion (−) in cubic yards of sand/yard of beach/month.
† No data.

TABLE 17

RATES OF ACCRETION AND EROSION, SELECTED BEACHES, OAHU*

BEACH	SECTOR	BEACH LENGTH (yards)	5/62–7/62 (2 mos.)	7/62–11/62 (4 mos.)	11/62–3/63 (4 mos.)	3/63–5/63 (2 mos.)	5/63–8/63 (3 mos.)
Laie	eastern	1700	+6.5	−5.7	+6.0	−3.5	−8.3
Hauula (N)	eastern	667	†	†	+6.5	−14.0	−1.6
Hauula	eastern	480	†	−1.2	−0.5	−1.5	+1.2
Punaluu	eastern	880	†	−1.2	+2.0	−4.5	−1.0
Kahana	eastern	1100	†	+31.5	+17.7	†	†
Kailua (N)	eastern	1175	+10.0	+3.5	−5.2	−1.5	+14.3
Kailua	eastern	1175	+8.5	−0.5	+6.2	−14.0	−1.0
Kailua (S)	eastern	1175	+3.0	+5.2	+5.2	−12.0	+9.3
Lanikai (S)	eastern	1850	+2.5	−0.3	+2.0	−21.1	+15.3
Waimanalo	eastern	3850	+5.0	−18.0	+7.7	−22.5	+9.3
Waimanalo (S)	eastern	3850	+4.0	−8.2	−0.7	+9.5	+7.3
Makapuu	eastern	333	+23.0	+0.7	−3.0	−32.0	+7.3
Sandy Beach	eastern	500	−4.0	−18.5	+15.7	−20.5	−3.6
Kahala	eastern	2080	†	−0.7	+1.2	−1.5	+1.3
Natatorium	eastern	410	†	−1.0	+7.5	−12.0	−1.0
Kuhio	eastern	1200	†	−2.5	+0.2	−1.5	+2.3
Ewa	western	3000	+3.5	−1.5	−4.5	0	+1.6
Kalanianaole	western	167	+176.0	−73.2	−7.0	+42.0	−0.3
Maili	western	3300	−5.0	−5.2	−24.2	+28.5	+15.0
Pokai	western	200	+18.0	−5.5	−6.7	+0.5	+18.6
Makaha	western	670	+32.5	−20.0	−39.0	+32.0	+20.0
Keawaula	western	1200	+89.5	−35.2	−8.0	+58.0	+18.0
Erdman	northern	700	†	−5.0	+10.5	−12.0	+1.3
Mokuleia	northern	1000	†	+2.0	−8.5	−1.5	+4.6
Waialua	northern	33	†	−2.0	+7.5	+14.0	+11.6
Kawailoa	northern	600	†	−8.0	−4.5	+21.0	+5.3
Waimea	northern	275	−24.0	−9.7	+12.2	−97.0	+10.0
Sunset	northern	1600	+55.0	−22.5	+20.7	−9.5	+3.6

* Rates of accretion (+) and erosion (−) in cubic yards of sand/yard of beach/month.
† No data.

TABLE 18

RATES OF ACCRETION AND EROSION, SELECTED BEACHES, MOLOKAI*

BEACH	BEACH LENGTH (yards)	6/62–8/62 (2 mos.)	8/62–11/62 (3 mos.)	11/62–3/63 (4 mos.)	3/63–6/63 (3 mos.)	6/63–9/63 (3 mos.)
Halawa	85	†	−7.6	−3.0	+11.6	+31.3
Kanaha	75	−1.5	+1.3	+1.0	0	−0.6
Onealii	200	+1.5	0	−0.7	0	+0.3
Kapukuwahine	600	−24.5	0	−40.0	+16.0	+26.3
Kamakaipo	1300	†	+1.6	−3.6	+6.0	−0.6
Papohaku	3100	−130.5	−102.5	−25.7	+55.3	−14.3
Kepuhi	250	+22.5	−2.6	−22.7	+20.0	+7.3
Kawaaloa	600	+30.0	−128.6	+132.0	−41.3	+13.0

* Rates of accretion (+) and erosion (−) in cubic yards of sand/yard of beach/month.
† No data.

TABLE 19

RATES OF ACCRETION AND EROSION, SELECTED BEACHES, LANAI*

BEACH	BEACH LENGTH (yards)	6/62–9/62 (3 mos.)	9/62–12/62 (3 mos.)	12/62–4/63 (4 mos.)
Halulu	700	†	−13.0	+2.2
Hauola	400	−7.3	+6.6	−0.2
Hulopoe	450	−2.0	−3.0	+2.0
Polihua	1600	−2.3	−40.7	−49.7

* Rates of accretion (+) and erosion (−) in cubic yards of sand/yard of beach/month.
† No data.

TABLE 20

RATES OF ACCRETION AND EROSION, SELECTED BEACHES, MAUI*

BEACH	BEACH LENGTH (yards)	4/62–6/62 (2 mos.)	6/62–9/62 (3 mos.)	9/62–2/63 (5 mos.)	2/63–6/63 (4 mos.)	6/63–9/63 (3 mos.)
Hana	233	−14.0	+9.0	−2.6	−1.5	+7.0
Hamoa	333	†	−1.7	−8.8	−1.0	+12.7
Puu Olai	1100	−1.0	+0.3	+29.6	−27.0	−13.3
Makena	333	+16.0	−18.7	+3.2	+1.0	−3.3
Keawakapu	900	+4.5	+3.0	−11.0	+10.5	+5.3
Kalama	2375	−1.5	−2.3	+0.2	−0.5	+1.7
Kihei	1362	−28.0	−7.3	−10.2	+19.7	−2.0
Maalaea	1362	−9.0	−8.3	+5.8	−6.7	+13.3
Olowalu	1760	−12.0	−2.3	+6.0	−15.7	+8.3
Makila	200	0	−0.3	−0.6	0	+5.0
Hanakaoo	1500	−17.0	−2.0	+2.4	−3.5	+1.7
Kaanapali	440	†	†	−4.2	+8.2	+8.0
Napili	333	†	−19.7	−14.0	+15.0	+15.3
Fleming's	200	†	+4.7	+2.4	−2.5	+1.7
Honokahua	500	+13.0	+3.3	−5.6	+12.5	−15.3
Wai Paoko Kaio	1675	+4.0	+0.6	0	−0.2	0
Kahului Harbor	525	†	−29.6	+10.4	−5.2	−5.7
Kahului	1520	−14.0	+9.0	+11.0	−12.2	+12.7
Papaula	700	+20.0	−5.0	−11.6	+8.5	−9.3
Paia	433	−5.0	+3.3	−3.4	+3.0	+9.0

* Rates of accretion (+) and erosion (−) in cubic yards of sand/yard of beach/month.
† No data.

TABLE 21

RATES OF ACCRETION AND EROSION, SELECTED BEACHES, HAWAII*

BEACH	BEACH LENGTH (yards)	4/62–6/62 (2 mos.)	6/62–9/62 (3 mos.)	9/62–1/63 (4 mos.)	1/63–4/63 (3 mos.)	4/63–7/63 (3 mos.)
Waipio†	1320	−66.0	−19.7	+9.2	+18.7	−43.3
Hilo	500	‡	+0.3	+0.5	+0.7	−0.7
Kaimu	333	‡	+0.3	−3.5	+9.7	−8.0
Punaluu	266	‡	−0.3	−0.5	−0.3	+1.7
Hookena	220	‡	−0.3	−2.5	−0.7	−1.0
Kealakekua	175	0	−2.3	−1.2	+0.3	+0.7
Disappearing Sands	100	+10.0	−0.7	−6.5	−0.3	+5.0
Hapuna	500	−4.5	−15.3	−0.7	−9.0	+27.0
Kawaihae	90	−2.5	+1.3	−1.0	0	−2.7

* Rates of accretion (+) and erosion (−) in cubic yards of sand/yard of beach/month.
† Rates of change are not representative for the entire beach. Applicable only to vicinity of range.
‡ No data.

mencement of the northeast trades, began to erode.

Littoral Transport

The organic sand-size constituents of the Hawaiian littoral sands are produced across the entire width of the reef and are transported landward by series of tortuous channels across reef flats, and by depressions or pockets on the reefs themselves. On the beach and in near-shore waters they are mixed with inorganic terrigenous particles and moved along or on and off shore in response to waves and currents.

The lateral or alongshore transport of sand is limited, and alongshore transport distances of less than a few miles are the rule except in a very few cases, such as along the Mana Coastal Plain of southern Kauai, parts of southwestern Oahu, and the western coast of Molokai. Here the total volume of sand moving past a single point on the beach is appreciable, and the volume has been estimated by the U. S. Army Corps of Engineers to be approximately 20,000 cubic yards per year. But it is more likely that in most areas of the Hawaii coasts the along-shore transport is not even one-tenth this amount. Littoral cells generally are small and bounded by numerous rocky points and cliffs, and, as evidenced by the distribution of sand bodies within the cells and by underwater observations at the cell boundaries, very little sand escapes around the headlands and promontories that bound the cells.

Evidence indicates that within the littoral cells, however, there is an appreciable littoral transport of sand *perpendicular* to the coast. Our measurements show that several thousands to several tens of thousands of cubic yards of sand per mile of coastline are continually in motion, either moving on shore or off shore, as shown by rates of erosion and accretion, depending upon wave and current conditions. For example, during the Kona storms of the winter of 1962–63 nearly 2 million cubic yards of sand were eroded from the beaches between Pearl Harbor and Kaena Point, Oahu—an average of 62,000 cubic yards put into motion per mile of coastline. During the following spring and summer, 1.8 million cubic yards of sand were transported back onto those same beaches, or an average of 55,000 cubic yards of sand per mile of coast.

On the eastern coast of Oahu between Kahuku Point and Makapuu Head, more than 500,000 cubic yards of sand were eroded from the beaches during March, April, and May 1963, or an average of 10,000 cubic yards transported per mile of coast. During the period just prior to this erosion (November 1962–March 1963) 443,000 cubic yards were added to the same beaches, or more than 9,000 cubic yards transported per mile of coast. Similar rates of littoral transport were measured for the northern Oahu beaches.

For the transport of 50- or 60-thousand cubic yards of sand per mile of coast during a 2- or

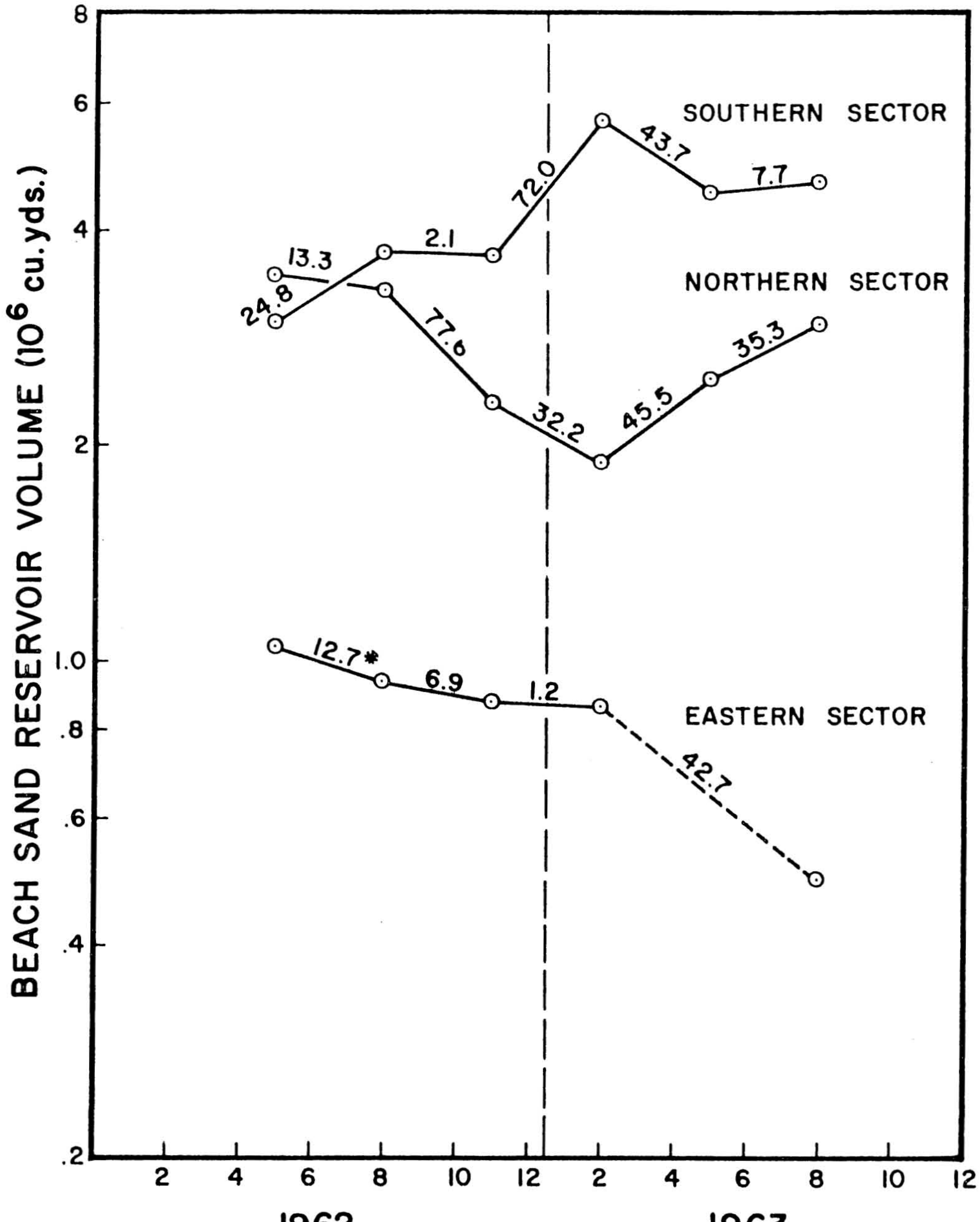

FIG. 5. Seasonal fluctuations in beach sand reservoirs, selected beaches, eastern, northern, and southern sectors, Kauai. (*Rates of accretion and erosion in cubic yards/yard of beach/month.)

3-month period, certain particular wave conditions are necessary.[3] The commencement of steep *Kona waves* along the western sectors of the various Hawaiian islands activates beach erosion. When these waves cease running, the western beaches accrete. Accretion usually is accompanied by *Southern Swell* or near-quiescent conditions.

[3] See Appendix, Hawaiian Wave Types.

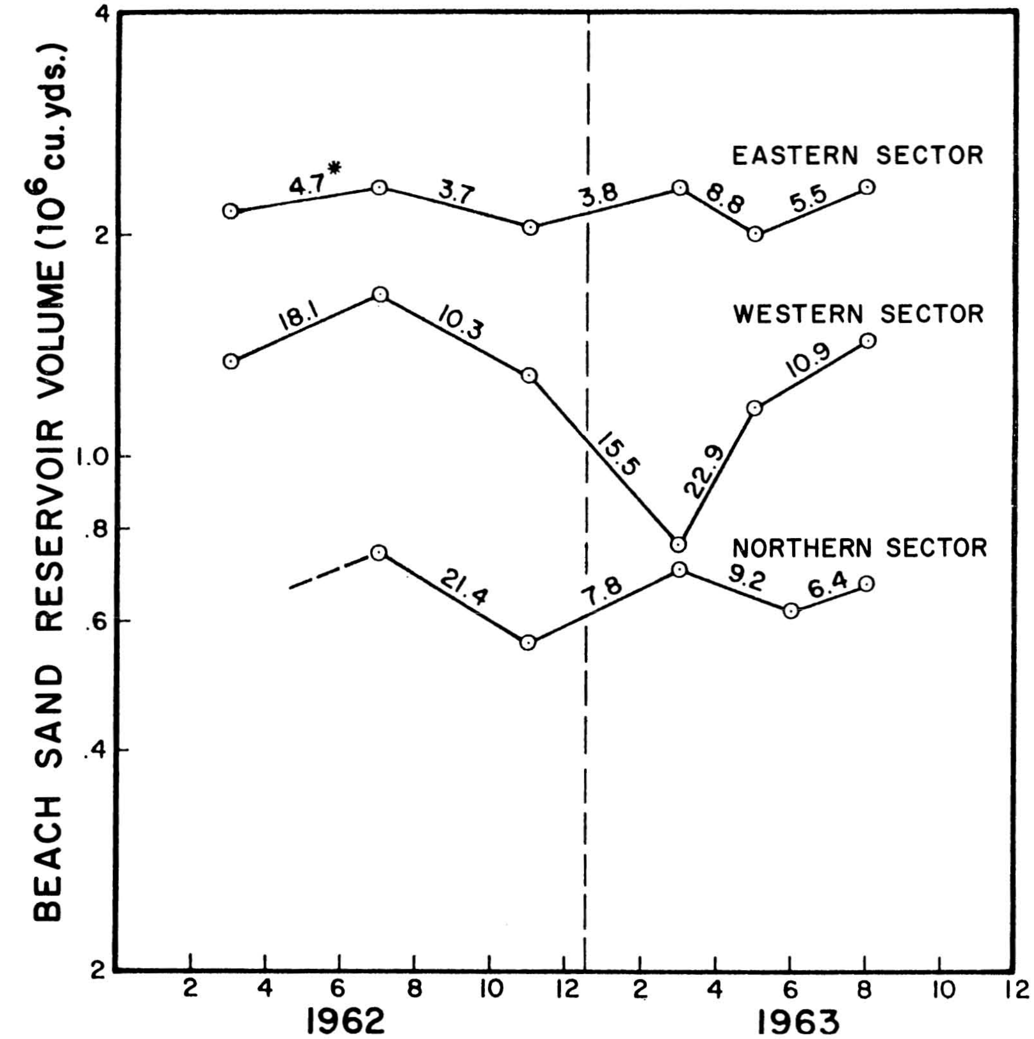

FIG. 6. Seasonal fluctuations in beach sand reservoirs, selected beaches, northern, western, and eastern sectors, Oahu. (*Rates of accretion and erosion in cubic yards/yard of beach/month.)

Along the eastern and northern sectors of the Hawaiian Islands beach erosion commences when steep, high waves of the *Trade Wind Swell* or the *North Pacific Swell* arrive. During periods of flat *Trade Wind Swell* or *North Pacific Swell,* or when the trade winds are disrupted by the flow of westerly air, the beaches generally accrete.

CONCLUSIONS

1. Much of the littoral sand found around the Hawaiian Islands is held on the beach as a beach sand reservoir. The larger individual beaches may contain 10^6 cu yd of sand between mean sea level and the landward edge of the beach. A more average volume for a typical Hawaiian beach is approximately 10^5 cu yd. The largest beach reservoirs are Papohaku, Molokai (10^6 cu yd), Polihua, Lanai (5×10^5 cu yd), and Polihale, Kauai (3×10^6 cu yd).

2. More beach sand exists on the island of Kauai than on any other Hawaiian island (1.4×10^7 cu yd). Oahu has the next largest total beach sand reservoir (10^7 cu yd). The average volume of the beach sand reservoirs

per mile of coast for these two islands is 1.2×10^5 cu yd and 0.8×10^5 cu yd, respectively. The island of Hawaii has the smallest total beach sand reservoir (1.6×16^6 cu yd) and the smallest volume per mile of coastline (5.5×10^3 cu yd).

3. Large volumes of sand are found in the nearshore zone either on the reef flats in sand pockets and depressions, or in sand channels that cut across the reef, or in large sand deposits off the mouths of coastal streams and rivers. For a small reef area, measurements have been made showing that this nearshore sand reservoir out to a depth of -40 ft MLLW is on the order of 5×10^4 cu yd of sand per mile of coast. Within a similar depth range along coastal areas with large nearshore sand channels, volumes for the nearshore sand reservoir of 10^6 cu yd of sand per mile of coast have been measured.

4. Seasonal fluctuations in the beach sand reservoir are very pronounced. Beach volume rates of change at several tens of cubic yards of sand per linear yard of coast per month have commonly been measured. Rates of change of up to 10^2 cu yd of sand per linear yard of coast per month are not uncommon. During 1962–63 the highest beach volume rates of change occurred on the northern coast of Kauai, the western coast of Oahu, and the western coast of Molokai.

5. Fluctuations in the beach sand reservoir volume are particular for various sectors of the various islands, and are correlated with the amount and type of wave energy that reaches the beaches. Those beaches opening to westward are eroded upon the commencement of the westerly (winter) winds due to the arrival of the steep, high *Kona waves* commonly associated with those winds. During the summer period of northeasterly winds and waves, these beaches accrete. Beaches lying on the eastern or windward sides of the Hawaiian Islands are completely dependent upon the *Northeast Trade Swell,* and their beach sand volumes fluctuate accordingly. When the strength of the *Northeast Trade Swell* diminishes, as during the development of westerly winds, the eastern beaches accrete. During steep *Northeast Trade Swell* or *North Pacific Swell* these same beaches undergo rapid erosion.

6. The following data appear pertinent to the quantitative balancing of the littoral sand budget along the coasts of the Hawaiian Islands:

a. LITTORAL SAND SOURCES. An average sand contribution to an Hawaiian littoral cell may be $2\text{–}5 \times 10^3$ cu yd per mile of coast per year. Depending upon the locality, the following rates are applicable:

(1) *Stream runoff.* For Waimea, Kauai, perhaps 2.5×10^4 cu yd per year; for other Hawaiian streams, much less.

(2) *Biological activity.* No direct measurements; from consideration of littoral transport rates, an average of $1\text{–}5 \times 10^3$ cu yd of sand per mile of coast per year for well-developed reef areas.

(3) *Coastal erosion.* Locally, $10^2\text{–}10^3$ cu yd of sand per mile of coast per year.

(4) *Wind.* Negligible.

b. LITTORAL TRANSPORT RATES

(1) *Alongshore.* Average: 2×10^3 cu yd per year. Locally, possibly as high as 10^4 cu yd per year.

(2) *Normal to shore.* Measured values of 2×10^4 cu yd per mile of coast per month are common. Average is probably 5×10^3 cu yd per mile of coast per month.

c. LITTORAL SAND LOSSES

(1) *Paralic sedimentation.*

(a) *Nearshore.* Average, perhaps 2×10^3 cu yd yer mile of coast per year (attritional products of the beach sand: silt and very fine sand).

(b) *Coastal progradation.* Locally, 5×10^3 cu yd per year; average, 10^3 cu yd per mile of coast per year.

(2) *Wind.* Locally, high rates of loss, perhaps 2×10^3 cu yd per mile of coast per year. On the leeward side, loss negligible.

(3) *Beachrock formation.* Small, perhaps 10^2 cu yd per mile of coast per year.

7. To balance the littoral sand budget, the estimated average sand contribution within each littoral cell of $2\text{–}5 \times 10^3$ cu yd of sand per mile of coast per year must be balanced by the yearly loss from the littoral cell due to paralic sedimentation, wind, or beachrock formation. Rates of alongshore transport may also equal these rates if the alongshore-transported sand is destined to be removed from the littoral

cell. The measured high rates of littoral transport normal to the beach (2×10^4 cu yd of sand per mile of sandy coast per month) represent within-cell transport of an intermittent nature.

8. There is a definite decrease in the general intensity and magnitude of the littoral processes throughout the Hawaiian Islands from the northwest to the southeast. Both the absolute values of the littoral sand reservoirs and the rates of change of those reservoirs decrease continuously from Kauai to Hawaii. These phenomena can be partially explained by the increasing youth of the islands to the southeast and consequently the better development of reef platforms and fringing reefs on the older islands to the northwest. A larger reef structure would allow a greater biological production of sand and could account for the greater volumes of the sand reservoirs on the older islands and for the progradation of the shorelines to the northwest. Real differences may also exist in the total amount of wave energy reaching the individual Hawaiian islands.

APPENDIX

HAWAIIAN WAVE TYPES

Almost all of the energy that is available along the coasts of the Hawaiian Islands for deforming beaches and transporting sediment arrives in the form of ocean waves. These waves are generated in all parts of the Pacific Basin, some even in the South Indian Ocean, and, after a complex history, they arrive in the Hawaiian Islands exhibiting a wide variety of heights, lengths, periods, and velocities. At any one time several generating areas may be supplying waves simultaneously, and this consideration along with the seasonal activity of certain generating areas, the interaction of various wave trains, the attenuation of waves over long distances, and the effect of local winds and waves on distantly generated waves, all result in a very complex wave pattern along the coasts of the Hawaiian Islands.

It is suggested from a study of available wind and wave data that the entire yearly wave spectrum in the Hawaiian Islands can be represented by a few generalized wave types, typified by a specific range of wave heights, periods, and directions of approach (Fig. A-1).

1. *Northeast Trade Wave.* These waves may be present throughout most of the year, but are largest between April and November when they usually dominate the local wave spectrum. They result from the strong trade winds blowing out of the northeast quadrant over long fetches of open ocean. These waves typically have periods of from 5 to 8 seconds, and heights of between 4 and 12 ft. The direction of approach may vary from north through southeast, but the most frequent direction of approach is either from the northeast or from the east. Generally, northeast trade waves are present from 90 to 95% of the time during the summer and from 55 to 65% of the time in the winter months (Marine Advisers, 1963 and 1964; Moberly and Chamberlain, 1964).

2. *Southern Swell.* During the winter season in the southern hemisphere (the summer season in the Hawaiian Islands) strong winds blowing over long fetches produce very large waves in the region adjacent to Australia, Antarctica, and in the southern Indian Ocean. These waves, after traveling distances measured in thousands of miles, arrive in the Hawaiian Islands as low, long-period waves from the southern quadrant. Typically, Southern Swell can be identified along the Hawaiian coasts because of its low height (generally, 1–4 ft) and long period (generally, 14–22 seconds). The direction of approach is from the southern quadrant (Snodgrass et al., 1966). In a typical year, Southern Swell arrives in the Hawaiian Islands during 53% of the time, usually during the months April through October.

3. *Kona storm wave.* Kona storm waves are generated by the interim winds associated with local fronts or Hawaiian lows of extra-tropical origin, as discussed above under meteorological considerations. These waves are neither frequent nor consistent, as they are associated with erratic westerly winds. However, since these waves may develop to a large size and may approach the Hawaiian Islands in a direction opposite to that of the normal wind and wave regime, they are extremely important in relation to beach accretion and erosion and to nearshore water circulation. Kona storm waves may approach the Hawaiian Islands from any direction between the southeast and the west, but the larger waves are usually from the southwest.

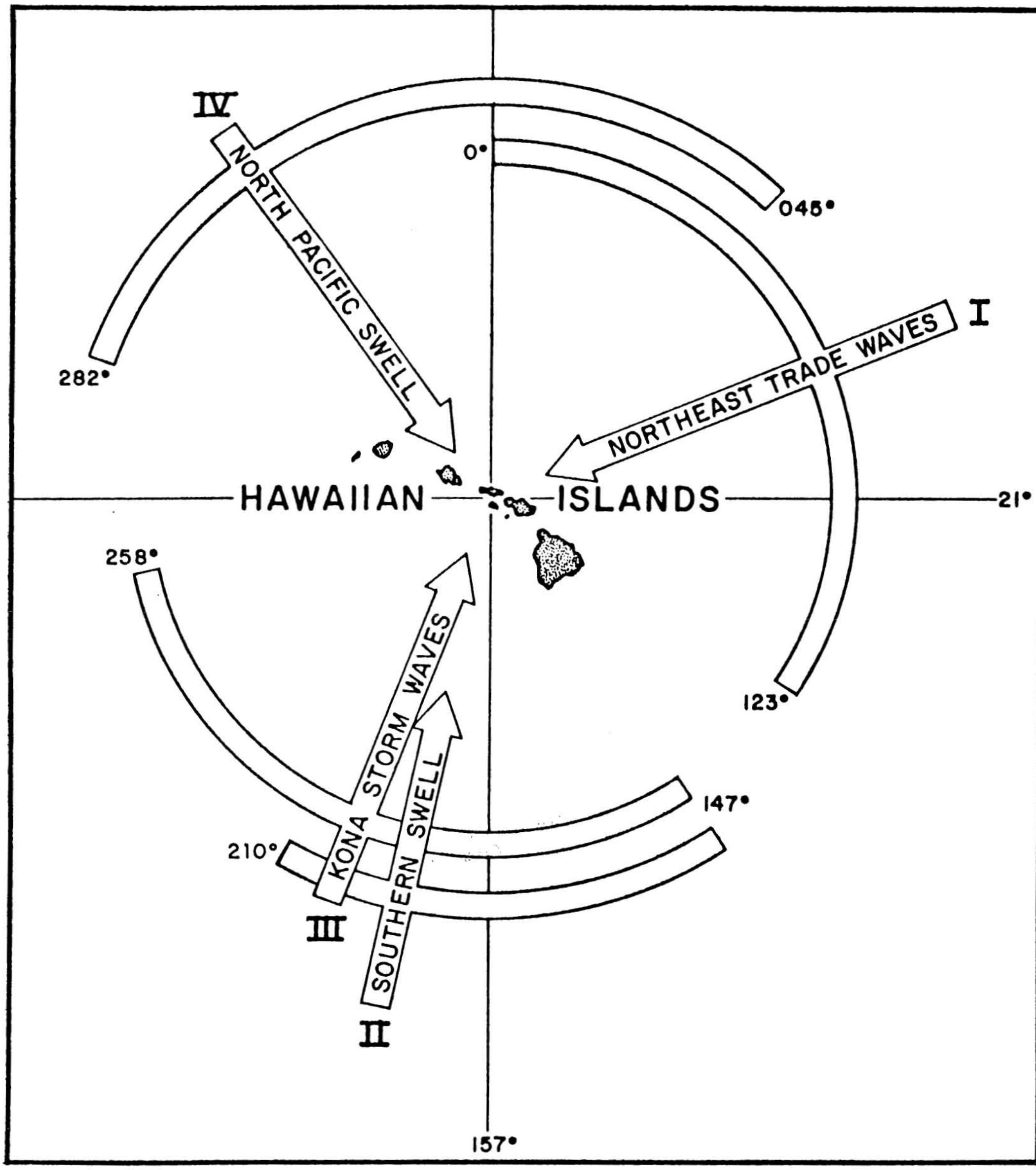

FIG. A-1. Hawaiian waves.

Commonly, periods range from 8 to 10 seconds, and heights from 10 to 15 ft. In a typical year, Kona storm waves may be arriving in the Hawaiian Islands during 9.3% of the time, usually during the winter months.

4. *North Pacific Swell.* Waves produced by storms in the Aleutian area and by mid-latitude lows may arrive in the Hawaiian area throughout the year, but they are largest and most numerous during the period October through May. They may approach from the northwest, north, or northeast, and typically have periods of about 10–15 seconds and heights of 8–14 ft. Some of the largest waves reaching the Hawaiian Islands are of this type.

In addition to the above four representative wave types into which the total yearly wave spectrum can be conveniently broken, there exist other wave types which are too difficult to identify or are insignificant to the nearshore zone and beaches, either because of their small magnitude or because of their infrequent occurrence. Foremost of these are *Typhoon Waves,* produced in the equatorial and southern latitudes during the passage of tropical storms. Usually, these waves approach from the southeast through the southwest and are most likely to occur in August and September.

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